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Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans

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Abstract The purpose of this study was to investigate the effect of concurrent strength and endurance training on strength, endurance, endocrine status and muscle fibre properties. A total of 45 male and female subjects were randomly assigned to one of four groups; strength training only (S), endurance training only (E), concurrent strength and endurance training (SE), or a control group (C). Groups S and E trained 3 days a week and the SE group trained 6 days a week for 12 weeks. Tests were made before and after 6 and 12 weeks of training. There was a similar increase in maximal oxygen consumption ($\dot{V}O_{2\,max}$) in both groups E and SE ($P < 0.05$). Leg press and knee extension one repetition maximum (1 RM) was increased in groups S and SE ($P < 0.05$) but the gains in knee extension 1 RM were greater for group S compared to all other groups ($P < 0.05$). Types I and II muscle fibre area increased after 6 and 12 weeks of strength training and after 12 weeks of combined training in type II fibres only ($P < 0.05$). Groups SE and E had an increase in succinate dehydrogenase activity and group E had a decrease in adenosine triphosphatase after 12 weeks of training ($P < 0.05$). A significant increase in capillary per fibre ratio was noted after 12 weeks of training in group SE. No changes were observed in testosterone, human growth hormone or sex hormone binding globulin concentrations for any group but there was a greater urinary cortisol concentration in the women of group SE and decrease in the men of group E after 12 weeks of training ($P < 0.05$). These findings would support the contention that combined strength and endurance training can suppress some of the adaptations to strength training and augment some aspects of capillarization in skeletal muscle.

Key words Muscle fibre type · Capillarization · Adenosine triphosphatase · Succinate dehydrogenase · Maximal oxygen consumption

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Introduction

Strength and endurance training have been performed concurrently in an attempt to improve performance in particular sports (Bell et al. 1991, 1997) and military tasks (Kraemer et al. 1995) as well as for rehabilitation from injury and cardiovascular disease (McCartney et al. 1991). It has also been shown that the addition of endurance training during the recovery from muscle graft surgery in rats can limit muscle hypertrophy (Esser and White 1990). The physiological stimuli directed to skeletal muscle as a result of strength training and endurance training are divergent in nature and it has been suggested that they may even be antagonistic to gains in strength (Hickson 1980; Dudley and Djamil 1985; Hunter et al. 1987). Recent research has shown some attenuation in muscle power and strength adaptations, after concurrent strength and endurance training compared to a single mode of training, that was related to a lack of change of some aspects of skeletal muscle morphology and the response of certain serum hormones to exercise (Kraemer et al. 1995). Research in our laboratory has shown some support for a lack of change in skeletal muscle cross-sectional area (Bell et al. 1991) and an elevated urinary free cortisol concentration (UC) in women (Bell et al. 1997) after performing combined strength and endurance training. Thus, the majority of research has supported the contention that the adaptations to strength training are different when combined with endurance training and the physiological basis for this may be linked to an interaction between an elevated

catabolic hormonal state leading to a reduced change in skeletal muscle cross-sectional area.

Conversely, other research has shown a compromise in some aspects of endurance (Nelson et al. 1990), a synergistic or additive effect in some muscle adaptations (Sale et al. 1990b), or a compatibility in certain adaptations as a result of concurrent strength and endurance training (McCarthy et al. 1995). In addition, Stone et al. (1997) have found that increases in citrate synthase activity as a result of endurance training were reduced when rat skeletal muscle was undergoing hypertrophy subsequent to synergist ablation. Thus, some controversies exist regarding the universal nature of the "interference effect" that has been described by Hickson (1980) in strength development when strength training is performed concurrently with endurance training.

Therefore, the purpose of this study was to investigate the physiological effects of concurrent strength and endurance training on strength, aerobic endurance, skeletal muscle properties and hormone concentrations. Measurements used to indicate the above variables were: one repetition maximum (1 RM) strength for leg press and knee extension, maximal oxygen consumption ($\dot{V}O_{2\,max}$), muscle morphology and capillarization, muscle metabolic enzymes (myofibrillar adenosine triphosphatase, ATPase, succinate dehydrogenase, SDH, and alpha glycerol phosphate dehydrogenase, αGPD), and, serum hormone concentration's (testosterone) T, sex hormone binding globulin, SHBG, human growth hormone, hGH) and UC. It was hypothesized that if compromised strength gains occurred as a result of strength training being combined with endurance training, there may be a higher catabolic state as evidenced by elevated cortisol concentrations and a lack of change in muscle fibre size.

Methods

Subjects

A total of 45 male and female volunteers were randomly assigned separately by sex into one of four groups: strength training only (S, 7 men, 4 women), endurance training only (E, 7 men, 4 women), concurrent strength and endurance training (SE, 8 men, 5 women), and a control group (C, 5 men, 5 women). The mean age, height, and body mass for all subjects was 22.3 (SD 3.3) years, 176.0 (SD 9.3) cm, and 73.4 (SD 11.6) kg, respectively. The volunteers were mainly physically active university students and all had had some experience with strength and endurance training. However, none were formally training to develop strength or endurance fitness at the time of entry into the study. One limitation to this study was the small sample size of each sex in the experiment groups. This project was approved by the Faculty of Physical Education and Recreation Research Ethics Committee.

Experiment design

The experiment design included 12 consecutive weeks of training in periods for all groups except C. Groups S and E trained 3 days a week (Monday, Wednesday and Friday) and group SE performed identical regimes of strength and endurance training on alternate days (6 days a week). The two types of training in SE were performed on different days as Sale et al. (1990a) have shown that same day strength and endurance training compared to training on different days limits strength development – which we wanted to avoid in this design. This experiment design resulted in a disproportionate amount of training in SE (6 days a week) compared to S or E (3 days a week). This design was chosen to minimize residual fatigue from training and potential issues of overtraining as confounding factors in any observable compromised training adaptations (see Dudley and Djamil 1985; Dudley and Fleck 1987). A 12-week duration was chosen for training as previous research has shown that a compromise in strength development appears between 7 and 12 weeks of concurrent training (Hickson 1980; Dudley and Djamil 1985; Hunter et al. 1987; Kraemer et al. 1995; Bell et al. 1998).

All physiological testing was conducted before and after 6 and 12 weeks of training with the exception of C group which was tested before and after 12 weeks only. This was because there were no changes expected in the dependent variables without any training and also to decrease the number of aversive measurements made on C and the associated costs (e.g. muscle biopsies, blood samples, etc.). The C was asked to refrain from beginning any formal exercise training programme, especially anything that involved strength and endurance training, for the duration of the study. All the women had normal menstrual function and none were taking oral contraceptives which were pre-requisites for participation in this study. The women were asked to report on their menstrual status so that the blood and urine samples were not obtained within ±3 days of the peak day (e.g. day 14 in a 28-day cycle) of the menstrual cycle.

Skeletal muscle analyses

Biopsies of skeletal muscle were taken from the lateral aspect of the right vastus lateralis muscle using the needle biopsy technique of Bergstrom (1962) adapted for suction (Evans et al. 1982). The tissue samples were immediately extracted from the biopsy needle, visually oriented to provide a cross-sectional orientation of the fibres, mounted in embedding medium on cork and frozen in isopentane cooled to near freezing in liquid nitrogen. The tissue was stored at −80°C until analysed. For all the muscle analyses, the tissue sections were cut at 6 μm in a Tissue-Tek Cryostat maintained at −20°C (Miles Laboratories, Elkhart, Indiana) and mounted on glass coverslips with aqua mountant after histochemical staining.

Quantitative histochemical procedures were used to determine the enzyme activity of myofibrillar-ATPase, SDH and αGPD in the identical single fibres of serial sections for all enzymes. The procedures and quantification of these assays have been detailed in several previous studies from our laboratory (Martin et al. 1985, 1992; Bell et al. 1991; Neary et al. 1995). The criteria for quantification of enzyme activity using histochemical staining procedures as outlined by Stoward (1980) were met in our previous research and also in the present study. All quantitative histochemical enzyme activities were performed in triplicate. Quantification of the reaction product (proportional to enzyme activity) against known densities was performed using a PSICOM 232 computer-assisted image analysis system (Perceptive Systems Inc., League City, Texas).

The basic hardware and software components of this system have been described in detail previously and the reliability and validity of using quantitative histochemical procedures to indicate the above enzyme reactions have also been previously discussed (Martin et al. 1985, 1992; Blanco et al. 1988; Blanco and Sieck 1992). Also, previous research in our laboratory has shown that these assays distinguish between enzyme activity in fast and slow twitch muscle fibres of different muscle motor units (Bell et al. 1992a; Martin et al. 1992). Muscle fibre cross-sectional area was measured from the myofibrillar ATPase stained sections using the same image analysis system described above. The cross-sectional area and all three quantitative histochemical anzyme assays were measured specific to types I and II muscle fibres as determined from the myofibrillar ATPase assay. This allowed evaluation of fibre-type-specific training adaptations in the same single muscle fibres of

types I and II muscle fibres. No further single fibre analysis of enzyme activity or morphological measurements specific to types IIa and IIb subtypes were made as the myofibrillar ATPase assay used was run at a single alkaline pH of 8.4 (Martin et al. 1992).

Viewing of capillaries in skeletal muscle tissue sections was accomplished according to the technique of Anderson (1975). The capillary to fibre ratio was determined from the number of capillaries around each fibre corrected for peripheral fibres by subtracting half the number of capillaries in the periphery from the total number of capillaries (Brodal et al. 1977). Mean fibre area was divided by the capillary to fibre ratio to indicate capillary density as reported by Hepple et al. (1997). Mean fibre area was calculated using the following equation: (type I area · % type I) + (type II area · % type II) (Bell and Jacobs 1990).

Blood and urine procedures

Blood samples (8 ml) from an antecubital vein were collected at rest after 48–72 h of no training to determine total serum concentrations of T, hGH and SHBG. The blood was allowed to clot for 15 to 20 min in vacutainer tubes (Becton and Dickinson) and centrifuged for 10 min at 3000 *g*. The serum was drawn off and frozen at −80°C until analysis. The blood samples were collected between 4 p.m. and 6 p.m. as this has been considered to be a period of relative stability for these serum hormones (Cumming 1987; Neary et al. 1994; Bell et al. 1997). Urine samples were collected to determine UC over a 24-h period. The UC was used since it has been shown that cortisol exhibits a circadian cycle as well as a pulsatile release throughout any given hour of the day or night (Cumming 1987; Neary et al. 1994; Bell et al. 1997). The urine samples were collected in 2-l polypropylene bottles at the residence of each subject during a 24-h period after no training for 24–48 h.

Any women from whom it was not suitable to take blood and urine samples due to the timing of their menstrual cycles (i.e. not within ± 3 days of the peak cycle day) were asked to give the blood and urine samples as soon as possible during the designated test period and after 48 h of no training. Total urine volume was measured in a graduated cylinder and a 10-ml sample was removed and stored at −80°C until analysis. Radioimmunoassay methods (Diagnostic Products Corporation, Calif.) were used to measure all hormones in the serum and urine in duplicate. The samples were counted for 1 min in a γ-counter (Wallac Wizard 1470, Fisher Scientific Inc., Ab.) and the counts per minute were fitted to a standard curve using a spline function to determine the final concentrations of each hormone. Final cortisol concentration was expressed relative to 24-h urine volume ($\mu g \cdot 24\ h^{-1}$). Coefficients of variation (CV) for intra-assay variability were deemed acceptable if less than 12% (CV) for the duplicate measures of all the hormones otherwise a re-analysis was made. All assay methods conformed to the procedures outlined by the manufacturers (INCSTAR, Stillwater, Minn.) and all samples were initially analysed using the same chemicals to reduce inter-assay variability.

Physiological tests

The $\dot{V}O_{2max}$ and ventilation threshold were determined using a standard incremental exercise protocol (starting at 60 W for 2 min followed by an increase of 40 W every 2 min) until the subject felt exhausted using a Monark cycle ergometer pedalled at 60 rpm. Gas exchange was monitored using a Horizon metabolic measurement cart (Sensor Medics, Calif.). Ventilation threshold was determined as the lowest point prior to a systematic increase of the pulmonary ventilation/carbon dioxide production ($\dot{V}_E/\dot{V}CO_2$) versus power output ($\dot{W}$) relationship (Bhambhani and Singh 1985) and was used to prescribe the intensity of the endurance training. Criteria for $\dot{V}O_{2max}$ included a peak and/or plateau ($\leq 100\ ml \cdot min^{-1}$) in oxygen consumption that was associated with a respiratory exchange ratio greater than 1.10, the age-predicted or known maximal heart rate and a subjective feeling of exhaustion. If these criteria were not met, a retest was performed to confirm the $\dot{V}O_{2max}$. Heart rate was determined using a Polar Pacer heart rate monitor (Polar Electro, Sweden) checked for accuracy using an electrocardiograph (Cambridge).

Strength was assessed with a voluntary 1 RM test for bilateral incline leg press (45° incline) and dominant leg unilateral knee extension, both through a range of knee joint motion of 90°. Upper body 1 RM strength measurements were not made as both the strength and endurance training programmes were directed towards the muscle groups of the lower body. The subjects performed a 5-min warm-up on a cycle ergometer followed by stretching and a light set of ten repetitions of the strength exercise. A second set of eight repetitions was performed at a higher load (approximately 70% of 1 RM). The subjects then completed two repetition sets of increasing loads decided by judgement of the investigators until only 1 repetition could be performed. This usually took three to five sets and was measured to the nearest 1.14 kg for knee extension and to 4.5 kg for bilateral incline leg press. From 2–3 min rest was allowed between sets and constant verbal encouragement was given to all the subjects.

Physical training programme

Strength training performed by groups S and SE used a combination of machine loading systems (Universal) and free weights including four lower body exercises that used the major muscle groups involved in cycling (double leg press, single leg knee flexion and extension, and double leg calf raises) and four upper body exercises (bench press, seated pulldowns, shoulder press and bicep curls) to provide an overall balanced programme. The intensity and amount of strength training was monitored, programmed, and progressively overloaded as in previous studies in our laboratory (Bell et al. 1997) using a computer software package (B.E. Software, Lincoln, Nebraska) based on multiple RM tests of all strength exercises. The strength training intensity was increased by approximately 4% every 3 weeks (i.e. mean of 72%–84% of 1 RM) and the number of repetitions and sets ranged between 4 to 12 and 2 to 6, respectively.

Groups E and SE performed aerobic endurance training on Monark cycle ergometers. Continuous endurance training was conducted twice a week and began at 30 min and progressed to 42 min (a 4-min increase every 4 weeks). The intensity was equivalent to the power output at ventilation threshold ($\dot{W} \approx 173\ W$) determined as described above. Interval sessions were performed once a week at a work to rest ratio of 3 min of exercise: 3 min of active recovery. The interval exercise intensity was equivalent to a power output of 90% $\dot{V}O_{2max}$ ($\dot{W} \approx 291\ W$) and began with four sets and increased by one set every 4 weeks until seven sets were completed. Training intensities were recalculated after 6 weeks ($\dot{W}$ at ventilation threshold $\approx 189\ W$ and $\dot{W}$ at 90% of $\dot{V}O_{2max} \approx 301\ W$). All the subjects wore Polar Pacer heart rate monitors to record heart rates for each endurance training session.

Group SE performed the strength and endurance training programmes as described on alternating days (6 days a week) for 12 weeks. Both strength and endurance training prescriptions were upgraded at the midpoint of the tests (6 weeks) to optimize the training intensity.

Statistical analysis

Statistical analysis of all dependent variables except for muscle morphology and enzyme activities were performed using separate three-way ANOVA to compare sex and all four experiment groups, before and after 12 weeks of training (time). In addition, separate three-way ANOVA were performed to compare sex and the three training groups before and after 6 and 12 weeks of training because C was not tested at 6-weeks. Separate four-way ANOVA were used to compare muscle fibre area and enzyme activities between fibre types (I and II), groups, sexes and training. Multiple comparisons were performed to determine differences due to significant main and interaction effects using a Newman Keuls analysis. The level of significance was preset at $P < 0.05$ for all analyses. The statistical software program used was Statistica (Statsoft, Okla.).

Results

There was a significant main effect for sex indicating that men had a significantly higher $\dot{V}O_{2\,max}$, unilateral knee extension 1 RM and bilateral leg press 1 RM than the women at all times but there was no sex by time interaction for these variables suggesting that the men and the women changed similarly with training (Tables 1, 2). There was significant group by time interaction indicating that groups E and SE increased $\dot{V}O_{2\,max}$ significantly following 12 weeks of training and these scores were higher than C and S at this time. The $\dot{V}O_{2\,max}$ of C was lower than S and E prior to training ($P < 0.05$) but this was considered to be an artefact following the random assignment. This was true whether the results were considered as absolute (litres per minute) or relative (millilitres per kilogram per minute) values and therefore only the absolute scores have been given in Table 1. The men and women of both S and SE showed significant increases in bilateral leg press and unilateral knee extension 1 RM following 6 and 12 weeks of training (Table 2). Group S had a significantly higher unilateral knee extension 1 RM compared with all other groups following 12 weeks of training. Group E showed no change in unilateral knee extension but a significant increase in bilateral incline leg press was observed after 6 weeks only. No significant changes in strength were observed in the control group.

Muscle morphology and quantitative enzyme activities are shown in Table 3. Since there were no differences between men and women in the adaptations to training the data from the two sexes has been combined to simplify the presentation. However, it should be noted that there was a main effect for sex indicating that muscle fibre areas of the men were larger than those of the women regardless of fibre type, group, or at any time of training ($P < 0.05$). There was also a significant main effect between fibre types for area indicating that type II muscle fibres were larger than type I fibres irrespective of group, sex and time. There was a group by time interaction that revealed a significant increase in the areas of types I and II muscle fibres after 6 and 12 weeks in S. There was also a significant increase in the area of type II muscle fibres after 12 weeks in SE. The area of type I muscle fibres of the control group was smaller than all the other groups after 12 weeks of training ($P < 0.05$). Also, the type II muscle fibres of C were smaller than those of the S after 12 weeks of training ($P < 0.05$).

There was a significant main effect between fibre type and enzyme activities indicating that myofibrillar ATPase and αGPD activities were significantly higher and SDH was significantly lower in type II compared to type I muscle fibres (Table 3). There were no significant sex

Table 1 The effect of differential training on maximal oxygen consumption ($\dot{V}O_{2max}$) before and after 6 and 12 weeks of endurance (*E*), strength (*S*) and combined strength and endurance (*SE*) training as well as in controls (*C*). *F* Female, *M* male

Group	Sex	$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)					
		Before		6 Weeks		12 Weeks	
		Mean	SEM	Mean	SEM	Mean	SEM
C	F[a]	2.64	0.13[b]	NA	NA	2.55	0.14[b]
	M	3.97	0.11[b]	NA	NA	3.88	0.19[b]
E	F[a]	2.71	0.34	2.96	0.32	3.05	0.30[c]
	M	4.32	0.23	4.44	0.23	4.53	0.24[c]
S	F[a]	2.84	0.17	2.77	0.28	2.67	0.36
	M	4.35	0.06	4.32	0.06	4.29	0.05
SE	F[a]	2.79	0.10	2.90	0.08	3.00	0.09[c]
	M	4.27	0.18	4.47	0.20	4.54	0.22[c]

[a] Women are significantly different to men $P < 0.05$, [b] Significantly different from groups S and E before and after 12 weeks, $P < 0.05$, [c] significantly different from before and significantly higher than group S after 12 weeks, $P < 0.05$

Table 2 Unilateral knee extension (*KE*) and bilateral leg press (*LP*) one repetition maximum (*1 RM*) before and after 6 and 12 weeks of endurance (*E*), strength (*S*) and combined strength and endurance (*SE*) training as well as in controls (*C*). *F* Female, *M* male

Group	Sex	KE 1 RM (kg)						LP 1 RM (kg)					
		Before		6 Weeks		12 Weeks		Before		6 Weeks		12 Weeks	
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
C	F[a]	18.2	1.8			20.0	1.8	165.9	30.0			180.0	16.4
	M	38.2	4.1			39.5	3.6	266.8	46.8			297.3	47.7
S	F[a]	17.3	1.4	24.1	1.8[b]	27.3	2.3[d]	151.4	25.9	185.9	20.0[b]	249.1	75.5[c]
	M	36.8	3.6	45.9	3.6[b]	48.6	3.6[d]	260.5	29.5	322.3	34.5[b]	393.6	28.6[c]
E	F[a]	19.5	1.4	21.8	2.3	22.3	1.4	125.0	14.1	170.5	10.0[b]	177.3	13.2[b]
	M	39.5	2.3	39.1	2.3	40.5	1.8	283.6	17.3	345.5	21.4[b]	353.2	20.0[b]
SE	F[a]	20.0	2.7	25.5	2.9[b]	28.2	2.7[c]	140.0	13.2	194.5	15.5[b]	257.3	14.5[c]
	M	35.9	3.2	41.4	2.7[b]	43.6	2.7[c]	276.8	21.8	330.9	20.5[b]	379.5	15.9[c]

[a] Significantly different from men, $P < 0.05$, [b] significantly different from before training, $P < 0.05$, [c] significantly different from before and higher than groups C and E after 12 weeks of training. $P < 0.05$, [d] significantly different from before and after 6 weeks of training and higher than groups C, E and SE after 12 weeks of training, $P < 0.05$

Table 3 Fast twitch (type II) slow twitch (type I) muscle fibre area and enzyme activity before, after 6 and after 12 weeks of endurance (*E*), strength (*S*) and combined strength and endurance (*SE*) training as well as in controls (*C*). Note that the muscle fibre area of the men was higher than for the women (main effect not indicated). *mATPase* Myofibrillar adenosine triphosphatase, *SDH* succinate dehydrogenase, *αGPD* alpha glycerol phosphate dehydrogenase

Group	Fibre type		Fibre area (μm^2)			mATPase ($OD \cdot min^{-1}$)			SDH ($OD \cdot min^{-1}$)			αGPD ($OD \cdot min^{-1}$)		
			Before	After 6 weeks	After 12 weeks	Before	After 6 weeks	After 12 weeks	Before	After 6 weeks	After 12 weeks	Before	After 6 weeks	After 12 weeks
C	II[a]	Mean	3470		3519	0.241		0.214	0.063		0.069	0.058		0.066
		SEM	614		637	0.007		0.011[b]	0.007		0.009	0.005		0.008
	I	Mean	2639		2780	0.185		0.172	0.085		0.083	0.038		0.036
		SEM	301		329[d]	0.008		0.009	0.008		0.010	0.006		0.008
E	II[a]	Mean	3494	3640	3877	0.228	0.207	0.207	0.080	0.085	0.088	0.063	0.049	0.061
		SEM	340	287	395	0.022	0.019	0.008[b]	0.008	0.008	0.007[b]	0.005	0.007	0.007
	I	Mean	3622	3852	4014	0.182	0.151	0.168	0.095	0.103	0.101	0.037	0.030	0.034
		SEM	301	292	277	0.022	0.024	0.024	0.012	0.008	0.009[b]	0.005	0.007	0.006
S	II[a]	Mean	3506	4024	4483	0.211	0.215	0.221	0.084	0.066	0.063	0.059	0.050	0.046
		SEM	480	498[b]	570[c]	0.024	0.025	0.028[e]	0.019	0.008	0.008	0.009	0.007	0.004
	I	Mean	3250	3791	4137	0.163	0.172	0.172	0.099	0.081	0.083	0.039	0.029	0.026
		SEM	429	386[b]	470[c]	0.019	0.020	0.022	0.015	0.010	0.011	0.008	0.007	0.003
SE	II[a]	Mean	3542	3755	4030	0.175	0.189	0.179	0.050	0.054	0.063	0.044	0.041	0.041
		SEM	292	355	379[b]	0.016	0.017	0.017	0.006	0.007	0.008[b]	0.004	0.003	0.003
	I	Mean	3575	3627	3950	0.134	0.144	0.142	0.072	0.075	0.082	0.020	0.018	0.020
		SEM	239	279	370	0.012	0.013	0.014	0.006	0.008	0.010[b]	0.003	0.003	0.003

[a] Type II fibre area was significantly higher than type I, $P < 0.05$, [b] different from before training, $P < 0.05$, [c] different from before and after 6 weeks of training and higher than type II fibres of group C, $P < 0.05$, [d] different from all other groups after 12 weeks, $P < 0.05$, [e] significantly higher than group SE, $P < 0.05$

differences between any enzyme activities. There was a significant group by time interaction effect that showed a significant decrease in the myofibrillar ATPase activity in type II muscle fibres of C and E after 12 weeks of training. The myofibrillar ATPase activity of type II fibres was significantly higher in S compared to SE after 12 weeks. There were no significant changes in αGPD activity in either types I or II fibres in any group or sex after training. There was a significant main effect due to training for SDH activity that was primarily a result of an increase in SE and E after 12 weeks of training.

The data in Table 4 has also been combined for the two sexes since there was no significant sex by time interaction. There was a significant group by training interaction effect for capillary to fibre ratio that revealed an increase for SE after 12 weeks of training which was significantly higher than C. There was a significant main effect for sex and a main effect for time regarding the quotient of mean fibre area and the capillary to fibre ratio indicating that the men were higher than the women (mean 1658 vs 1184), predominately due to a greater area of the muscle fibres in the men. There was also an increase in this variable after 12 weeks in all training groups (mean 1357 vs 1485).

All hormones are listed in Table 5. Serum T was higher in the men and SHBG was higher in the women (main effect, $P < 0.05$). No significant changes were observed in serum T, hGH or SHBG for either sex after training. There was a significant group by sex by time interaction for UC. The UC was significantly decreased in the men of E after 12 weeks of training and significantly increased after 6 and 12 weeks of training in the women of SE and resulted in a significantly higher UC compared to all other groups after 12 weeks.

Table 4 Comparison of capillary to fibre ratio and quotient of mean fibre area (*FA*) to capillary to fibre ratio (*C:F*) before, after 6 and after 12 weeks of endurance (*E*), strength (*S*) and combined strength and endurance (*SE*) training as well as in controls (*C*)

Group	Capillary per fibre ratio						FA/C:F (μm^{-2})					
	Before		After 6 weeks		After 12 weeks		Before		After 6 weeks		After 12 weeks	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
C	2.23	0.11	NA	NA	2.09	0.15	1350	181	NA	NA	1497	166
E	2.25	0.18	2.37	0.20	2.40	0.18	1514	87	1542	99	1588	118
S	2.66	0.17	2.43	0.16	2.67	0.14	1217	114	1460	101	1546	142
SE	2.52	0.13	2.50	0.14	2.82	0.19[a,b]	1433	94	1360	122	1462	129

[a] Significantly different from before training, $P < 0.05$, [b] significantly higher than control group after 12 weeks, $P < 0.05$

Table 5 Concentration of serum testosterone (*T*), human growth hormone (*hGH*), sex hormone binding globulin (*SHBG*) and urinary cortisol (*UC*) before, after 6 and after 12 weeks of endurance (*E*), strength (*S*) and combined strength and endurance (*SE*) training as well as in controls (*C*). *F* Female, *M* male

Group	Sex		T (nmol · l^{-1})			hGH (ng · ml^{-1})			SHBG (nmol · l^{-1})			UC (nmol · 24 h^{-1})		
			Before	After 6 weeks	After 12 weeks	Before	After 6 weeks	After 12 weeks	Before	After 6 weeks	After 12 weeks	Before	After 6 weeks	After 12 weeks
C	M	Mean	20.07		22.78	0.985		0.888	56.32		44.22	35.63		33.12
		SEM	3.81		3.61	0.127		0.183	26.00		13.64	9.74		8.11
	F	Mean	1.14		1.73	0.760		0.811	76.06		75.16	42.37		39.08
		SEM	0.21		0.35	0.057		0.047	20.33		15.89	10.38		8.53
E	M	Mean	17.09	18.24	19.17	0.830	0.831	0.784	49.57	48.83	55.01	70.16	57.49	38.45
		SEM	1.73	1.84	5.53	0.104	0.074	0.044	14.73	10.96	18.12	17.00	15.79	8.56[a]
	F	Mean	1.01	1.91	1.35	1.099	0.931	0.928	71.93	73.15	76.88	32.26	27.77	31.93
		SEM	0.14	0.62	0.31	0.186	0.108	0.154	11.69	19.83	15.16	11.37	7.09	13.47
S	M	Mean	17.13	17.82	19.28	1.997	1.371	2.091	41.53	42.25	39.13	63.67	52.61	61.13
		SEM	1.39	1.04	2.53	0.546	0.281	0.711	4.51	6.92	5.22	17.61	19.40	11.65
	F	Mean	1.01	1.91	1.35	0.760	1.036	0.698	88.16	84.63	72.27	42.39	38.75	40.24
		SEM	0.14	0.62	0.31	0.439	0.449	0.087	5.31	10.61	4.48	19.60	6.79	10.05
SE	M	Mean	6.41	18.90	18.83	0.958	1.214	0.933	34.29	36.98	34.68	53.96	53.60	53.57
		SEM	1.39	2.18	2.39	0.074	0.108	0.076	4.87	4.87	4.28	6.98	9.60	10.02
	F	Mean	0.94	1.04	0.97	1.567	1.563	1.052	76.22	77.28	76.34	45.32	38.75	83.13
		SEM	0.21	0.24	0.31	0.585	0.765	0.155	7.74	8.92	6.20	14.32	6.79[a]	15.35[a,b]

[a] Significantly different from before training, $P < 0.05$, [b] significantly higher than all other groups, $P < 0.05$

Discussion

The present study found that concurrent strength and endurance training resulted in several adaptations that were different from either strength or endurance training alone. Our results provided evidence of a reduced change in knee extension strength; a lack of skeletal muscle hypertrophy especially in type I fibres; and, a greater level of UC primarily in the women as a result of concurrent training. The data also showed that concurrent strength and endurance training may produce greater increases in the capillary to fibre ratio compared to either type of training alone. Furthermore, the increases in $\dot{V}O_{2\,max}$ were similar between concurrent strength and endurance training and endurance training only. Thus, our hypothesis that concurrent strength and endurance training would compromise adaptations to strength gains but not hinder changes in endurance was partially supported by the present study.

The interest in the drawbacks or benefits of concurrent strength and endurance training has been primarily from the sporting community but other applications have been extended to include the military (Kraemer et al. 1995) and patients with post myocardial infarcts (McCartney et al. 1991). There has also been some interest in the physiological effects of adding an endurance training stimulus to muscle undergoing compensatory hypertrophy (Stone et al. 1996) as well as to muscle recovering from a muscle graft (Esser and White 1990). Many athletes require a high degree of strength and endurance for optimal performance (Bell et al. 1997, 1998). Also, many activities of daily living and rehabilitation strategies necessitate some degree of development in both strength and endurance. Most of the research has shown that short-term (less than 7–10 weeks), concurrent strength and endurance training can result in similar adaptations in both strength and endurance (Hickson 1980; Hunter et al. 1987; Bell et al. 1991). However, this later research and others (Dudley and Djamil 1987; Hortobagyi et al. 1991; Hennessy and Watson 1994; Kraemer et al. 1995; Bell et al. 1998) have shown a compromise in strength gains after approximately 7–12 weeks of simultaneous strength and endurance training.

The mechanisms underlying a compromise in strength training have not yet been conclusively demonstrated but possible explanations include a higher catabolic state as a result of elevated cortisol concentrations, a reduced gain in skeletal muscle hypertrophy, or even the possibility of an overtrained state (Dudley and Fleck 1987; Bell et al. 1991, 1997; Kraemer et al. 1995). It is possible that mechanical stress and the potential for eccentric muscle damage may be higher with run training compared to cycle training and these may be factors underlying adaptations to concurrent training. It is also important to note that not all research that has investigated concurrent strength and endurance training has shown a compromise in strength gains and associated adaptations (Nelson et al. 1990; Sale et al. 1990b; McCarthy et al. 1995). The possible reasons for the discrepancies include differences in the type of strength training (e.g. isokinetic vs free weights), experimental design (e.g. single-leg training design), subject sample (e.g. trained vs untrained) and the design of the training programme.

The present study found a similar increase in bilateral leg press 1 RM after strength training and concurrent

strength and endurance training but a greater increase in unilateral knee extension 1 RM occurred after strength training only. This apparent contradiction of adaptations in strength may have been due to the differences between these two exercises. Bilateral leg press has a pattern of multi-joint and multiple muscle movement that may have been less susceptible to any possible interfering effects of being combined with cycle endurance training, compared to the pattern of the unilateral single joint knee extension movement that involves less musculature but which matched more closely the cycle endurance exercise that was performed concurrently.

Kraemer et al. (1995) have shown a similar increase in double knee extension with concurrent strength and endurance training and strength training only but a greater increase in double leg press with strength training compared to concurrent training. This latter research has also suggested that this incompatibility may be a function of the movement pattern and the single versus multiple joint exercises being tested. Other research has shown compromised strength gains in both unilateral and bilateral leg exercises (Dudley and Djamil 1985; Hunter et al. 1987; Hortobagyi et al. 1991; Bell et al. 1998). It is also important to point out that endurance training resulted in an increase in knee extension and leg press 1 RM after 6 weeks with no further increases after 12 weeks. This would suggest that cycle endurance training may improve the strength of the knee and hip extensors which has been previously demonstrated by Rosler et al. (1986).

There has been little support for the suggestion that strength training may interfere with aerobic endurance adaptations when performed concurrently (Nelson et al. 1990), and most research has shown similar gains in $\dot{V}O_{2\,max}$ (Hickson 1980; Hunter et al. 1987; Sale et al. 1990b; Kraemer et al. 1995; McCarthy et al. 1995; Bell et al. 1997). The present study supports these latter findings. It seems that the addition of endurance training and the associated central and peripheral adaptations that would occur, are not negatively influenced by additional strength training despite other research that has shown a decrease in mitochondrial volume density with strength training (MacDougall et al. 1979) and a lack of change in $\dot{V}O_{2\,max}$ during the final 11 weeks of a 22 weeks concurrent strength and endurance training programme (Nelson et al. 1990).

It is possible that a reduced change in aerobic endurance parameters may occur with concurrent training of durations greater than 12 weeks (Nelson et al. 1990). However, similar changes in aerobic endurance have also been observed after longer term training of 22 weeks (Sale et al. 1990b). Thus, it would seem that the stimulus resulting from endurance training is potent enough to override or delay any interference factors as a result of endurance being combined with strength training programmes of less than 12 weeks in duration.

Muscle fibre hypertrophy is a common adaptation that has been found to occur as a result of heavy strength training (Enoka 1988; Kraemer et al. 1988). It has been suggested that a lack of change in the size of skeletal muscles may be an underlying reason for the depressed gains in strength after concurrent strength and endurance training (Bell et al. 1991; Kraemer et al. 1995). Furthermore, it has been shown that this lack of hypertrophy of muscle fibres may be specific to different fibre type populations (Kraemer et al. 1995). Our findings would suggest that the dissimilar gains in the size of muscle fibres between strength training and concurrent strength and endurance training occurred in both types I and II fibres but was more pronounced for the type I fibres as indicated by a lack of change in the areas of type I fibres after concurrent training. This was similar to the findings of Kraemer et al. (1995) and may have been partly due to the oxidative stress imposed on the muscle and the need to optimize the kinetics of oxygen transfer as a result of the addition of endurance training to strength training.

No distinction was made between the muscle fibre area of the type II subtypes (i.e. IIa, IIb or IIc fibres) and the possible effect on these fibres cannot be determined from the present study. Using computer tomography (CT) scanning (Bell et al. 1991) other research in our laboratory has shown a depressed rate of increase in the cross-sectional area of the whole quadriceps as a result of concurrent strength and endurance training. Sale et al. (1990b) have found similar increases in the cross-sectional area of knee extensor whole muscle using CT scanning but no change in the area of slow or fast twitch muscle fibres from biopsies of the vastus lateralis of the same muscle after concurrent training. Thus, our findings provide some support for the contention in other studies that combining strength and endurance training may have depressed skeletal muscle hypertrophy and that this may have been linked to an enhanced catabolic state as a result of elevated cortisol concentrations (Kraemer et al. 1995; Bell et al. 1997).

There is some controversy as to whether or not strength training can influence the activities of muscle metabolic enzymes (Tesch 1988). Research by others has shown increases, no change or decreases in enzyme markers specific to contractile activity, glycolysis and aerobic metabolism (for reviews see Tesch 1988; Abernethy et al. 1994). Conversely, endurance training has been shown to improve muscle oxidative potential as indicated by a variety of metabolic enzymes related to aerobic metabolism (Holloszy and Coyle 1984). There has been little research that has attempted to discern changes in metabolic enzymes as a result of concurrent training or the lack thereof, especially when expressed specific to populations of types I or II muscle fibres.

The present study used quantitative histochemical analyses to determine changes in contractile (myofibrillar ATPase), glycolytic (αGPD) and oxidative (SDH) metabolic enzyme markers specific to the same single fast and slow twitch muscle fibres that corresponded to the measurements of fibre area. The anticipated differences in myofibrillar ATPase, αGPD and SDH activity between types I and II fibre types were observed. Concurrent strength and endurance training had no effect on myofibrillar ATPase activity in either

fibre type but there was a decrease in type II myofibrillar ATPase activity after endurance training, suggesting that concurrent training was able to counteract the possible decrease in this enzyme activity as a result of endurance training. The reason for this may be that certain types of strength training have been shown to increase myofibrillar ATPase activity in some studies (Thorstensson et al. 1976; Bell et al. 1992b) and, in the present study, the myofibrillar ATPase activity was higher in S compared to SE after 12 weeks of training.

There was a main effect of training on SDH activity. Examination of these findings shows that both E and SE had an increase in SDH activity after 12 weeks of training. Although not statistically different, it is interesting that SE had a greater relative increase overall (approximately 14%–26% for types I and II fibres) compared to E group (approximately 6%–10% increase). Sale et al. (1990b) have shown an additive effect for increases in citrate synthase when endurance training was combined with strength training. Conversely, Nelson et al. (1990) have demonstrated a lack of increase in citrate synthase activity with concurrent strength and endurance training.

There were no changes in αGPD, a marker of anaerobic metabolism (Martin et al. 1985), in either muscle fibre type as a result of any type of training performed in the present study. Previous research has shown increases, no change or decreases in some enzymatic markers of glycolysis as a result of strength and endurance training (Tesch 1988; Abernethy et al. 1994). Since the same muscle fibres were analysed for both metabolic enzymes and muscle fibre size, our findings would suggest that there was a decrease in metabolic support to the hypertrophying muscle fibres in S and either a maintenance or an increase in metabolic enzyme support in E or SE where muscle hypertrophy was less or absent.

The influence of combined strength and endurance on muscle capillarization has not been previously studied. Research has shown that endurance training (Andersen 1975; Andersen and Henriksson 1977; Brodal et al. 1977) and extreme strength training for body building (Schantz and Henriksson 1983; Bell and Jacobs 1990) or strength training in older adults (Hepple et al. 1997) can promote increases in some aspects of the capillaries perfusing skeletal muscle fibres. However, the expression of capillaries per fibre area has generally remained the same or has declined with strength training due to the hypertrophy of the muscle fibre (Bell and Jacobs 1990; Hepple et al. 1997). We found no significant changes in capillaries to fibre ratio and mean fibre area to capillary to fibre ratio after strength or endurance training alone but an increase in the capillary to fibre ratio was observed after concurrent training. The latter finding in combination with the increases in SDH activity would suggest a possible additive effect of concurrent training that was probably the result of the additional stress associated with this type of training.

Endurance training primarily demands an increased oxygen supply and metabolic waste removal while strength training stresses the recovery of depleted intramuscular adenosine triphosphate and creatine phosphate stores and removal of metabolic waste products both of which require an enhanced blood flow to and from the muscles involved. On the other hand, it may have also been the result of an overall greater amount of training being accomplished by SE (6 days a week) compared to S and E (3 days a week). This would help explain why the smaller amount of endurance training (3 days a week) used in the present study showed only modest increases in SDH and no change in capillarization. In addition the strength training programme followed in this study could not be considered to be similar to the amount and intensity of training that has been described as commonly performed by body builders (Bell and Jacobs 1990).

Glucocorticoids such as cortisol have been used to indicate the existence of a catabolic state that can lead to muscle protein degradation and may suppress T resulting in a decrease in the synthesis of muscle protein (Cumming 1987; Tsai et al. 1991; Neary et al. 1994; Bell et al. 1997). Conversely, anabolic hormones such as T and hGH, have been associated with enhanced synthesis of muscle protein leading to hypertrophy (Crowley and Matt 1996). It has been shown that concurrent strength and endurance training can elevate post-exercise serum cortisol concentration (Kraemer et al. 1995) and resting UC concentrations (Bell et al. 1997). In the same research, little or no changes in serum T concentrations have been observed (Kraemer et al. 1995; Bell et al. 1997). It is possible that free T concentration may have been elevated but the combined effect of no change in either total T or hGH would suggest that there was little change in the anabolic environment in the subjects of the present study. The present findings would indicate that UC concentration at rest was significantly elevated in the women as a result of concurrent strength and endurance training and this was coupled with no changes in serum T, hGH or SHBG concentrations in either sex. It was concluded from this that concurrent strength and endurance training can lead to an elevated catabolic state in women compared to performing the same strength or endurance training separately, or in comparison to men. However, endurance training only in the men resulted in a significant decrease in UC concentration compared to all other groups suggesting that combining strength training with endurance did not produce a similar decrease in cortisol. Thus, the present findings do provide some support for a differential response of UC concentration to concurrent strength and endurance training in both men and women.

Summary

The overall effect of concurrent strength and endurance training is that some interference with the development of strength may occur and this may be specific to particular movement patterns. The underlying reason for

the reduced gains in strength with concurrent training is partially due to a suppressed hypertrophic response in the muscle that may be related to an elevated catabolic state as indicated by higher concentrations of cortisol combined with no change in the concentration of anabolic hormones such as T or hGH. Conversely, some aspects of vascularization and oxidative enzyme activity as indicated by changes in capillary to fibre area and SDH activity may be improved to a greater extent with concurrent training compared to either strength or endurance training alone. It is suggested that similar gains in $\dot{V}O_{2\,max}$ can also be expected with concurrent training and endurance training only after 12 weeks. Thus, individuals that require the development of both strength and endurance for athletic, occupational or rehabilitation purposes, can be assured that short term (e.g. less than 7–10 weeks) concurrent training will promote increases in many aspects of strength and endurance. However, longer term training may lead to an elevated catabolic state, decreased skeletal muscle hypertrophy and impaired strength gains in some movement patterns. Conversely, concurrent endurance and strength training may promote increases in some aspects of capillarization that are greater than endurance training alone over the same period.

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